

PROTON DAMAGE TO SILICON AS A FUNCTION OF PROTON ENERGY

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INTRODUCTION

It is important for NASA to be able to predict the amount of damage produced in silicon electronic devices by the high energy protons which are present in space. To accomplish this, the dependence of the proton damage on the energies of the incident protons must be known. It was the purpose of the experiments reported in this paper to provide this information.


The energy dependence of the majority carrier removal rates in n- and p-type silicon single crystals for the energy range from 10.7 MeV to 53.25 MeV has been established by means of the determination of the Hall coefficient of the silicon. The results that have been obtained are directly applicable to majority carrier devices such as the junction field-effect transistor.

The various proton bombardments were conducted at the NASA Lewis Research Center cyclotron, Cleveland, Ohio, and the Oak Ridge Isochronous Cyclotron, Oak Ridge, Tennessee.

THEORY

Review of Theoretical Calculations

There have been several theoretical efforts to predict the damage produced by protons in silicon as a function of incident proton energy. At this point,

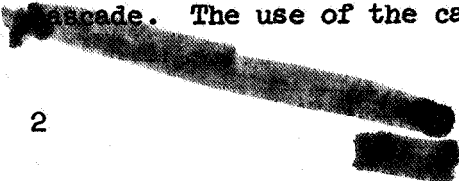


a qualitative description of three of the more recent theoretical attempts is in order.

Simon, Denny, and Downing (ref. 1) of the Space Technology Laboratories concluded that protons with energies exceeding approximately 10 MeV produce defects in the silicon lattice by elastic and inelastic scattering. At energies below 50 MeV, it was felt that Rutherford scattering produced the majority of the defects. It was proposed that above 50 MeV inelastic scattering becomes dominant in the defect production and that spallation of the target nucleus is the principal result of the inelastic scattering. It was further concluded that the use of a sharp ionization energy, that is, the energy of the primary recoil above which energy losses occur through ionization, was inappropriate for recoil damage calculations.

Baicker, Flicker, and Vilms (ref. 2) of RCA calculated the atomic displacement produced in silicon by assuming that Rutherford scattering describes the interaction between the proton and the silicon atom below 10 MeV and that the nuclear optical model describes the elastic scattering from 10 to 100 MeV. These calculations were performed through the use of optical model parameters for aluminum since practically no data existed for silicon and were carried out for several cases corresponding to different values for the ionization threshold energy from 13.5 to 200 KeV.

Saunders (ref. 3) in his doctoral dissertation for the Rensselaer Polytechnic Institute, performed calculations which made use of a complete optical model calculation of elastic and inelastic cross sections and employed the channeling theory of Oen and Robinson in the treatment of the displacement cascade. The use of the cascade model of Oen and Robinson takes into account



the inhomogeneity of the silicon crystal while the calculations mentioned previously were carried out by considering the silicon to be a homogeneous mass.

Defect Theory

When silicon is bombarded with high energy protons, defects are introduced which give rise to electronic energy levels in the forbidden gap of the material. However, such defects are not primary defects (interstitials and vacancies) but are usually some type of impurity complex as has been shown by Watkins and Corbett. Among the more common defect complexes in silicon are the oxygen-vacancy complex, phosphorus-vacancy complex, and the divacancy. The electronic energy levels produced in the forbidden gap can serve as acceptor levels which act as electron traps, donor levels which behave as traps for holes, and recombination centers for electrons and holes. In this instance, the majority carrier traps are the energy levels of interest.

In this series of experiments, the initial removal rates for majority carriers in silicon have been obtained before any appreciable shift of the Fermi level due to radiation-produced defects.

EXPERIMENTAL PROCEDURE

Czochralski-grown silicon which had been obtained commercially was used in this series of experiments. Bridge samples were cut by means of an ultrasonic cutter from 20-mil-thick silicon wafers oriented in the (111) direction. The samples were then mechanically lapped to a thickness of less than 10 mils (five mils in the case of the 10.7 MeV bombardments). Next, the silicon samples were etched in CP-4 etch. The tabs of the samples were then plated with nickel by means of an electrodeless chemical plating method. Finally,

leads were soldered to the nickel-plated tabs of the bridge samples; thereby, ohmic contacts to the silicon were obtained (see figure 1).

During irradiation the silicon samples were mounted in a chamber between the pole pieces of a magnet as is shown in figure 2. The silicon samples were irradiated in vacuum through a hole in one pole piece of the magnet. The beam current was maintained at approximately five millimicroamperes to avoid any large temperature rises in the sample. The sample thickness was such that the energy of the incoming protons was not appreciably reduced after the protons passed through the sample. The protons were collected by means of a Faraday cup mounted in the sample chamber (see figure 3).

The energies of the various proton beams were determined within ± 200 keV by means of magnetic analysis after the beams were extracted from the cyclotrons (refs. 4 and 5). The beam spot was determined by means of darkening several pieces of glass with the protons at various intervals during the bombardments.

The electrical measurements required for the Hall coefficient determinations were made during periodic interruptions of the irradiations. During these measurements, the magnetic field was maintained at 2500 gauss, and the pertinent voltage measurements were made with a precision digital voltmeter. During the bombardments, the magnetic field and the current to the sample were turned off.

RESULTS AND DISCUSSIONS

N-type, phosphorus-doped and p-type, boron-doped silicon single crystals were irradiated at room temperature by high energy protons at the following proton energies: 10.7 MeV, 16.7 MeV, 34.25 MeV, and 53.25 MeV. The removal rate of majority carriers was used to determine the amount of damage that was

produced in the silicon by the protons. Therefore, it was assumed that the majority carrier removal rate bears a linear relationship to the concentration of proton-produced defects. In figure 4, the electron concentration for an n-type sample with an approximate resistivity of $10\ \Omega\text{-cm}$ is plotted as a function of proton flux for a 34.25 MeV proton bombardment. Due to the introduction of acceptor levels into the forbidden gap of the silicon, the carrier concentration decreases monotonically with proton flux. The particular removal rate for this sample was -5.17 electrons/proton-cm. In figure 5, a similar plot is shown for a p-type, $10\ \Omega\text{-cm}$ sample. Here, the concentration of holes decreases due to the introduction of donor levels into the forbidden gap. The removal rate is -6.86 holes/proton-cm in this case.

The electron removal rate for n-type, $10\ \Omega\text{-cm}$ silicon is plotted as a function of proton energy in figure 6. The removal rates for several samples are plotted at the four proton energies previously mentioned. An average removal rate was calculated from the removal rates for the three samples at 10.7 MeV. From this average removal rate, a curve was determined which represents the expected removal rates if the damage produced in the silicon were due to Rutherford scattering only, that is, the damage is inversely proportional to proton energy. As can be clearly seen in this figure, the removal rates obtained experimentally are in excess of those expected for pure Rutherford scattering at the higher energies. A similar situation exists for $10\ \Omega\text{-cm}$, p-type silicon as is shown in figure 7.

The departure from the $\frac{1}{E_p}$ curve points out that Rutherford scattering accounts for less of the damage produced in silicon as the energy of the proton

is increased. It is felt that the increased damage at the higher proton energies is probably due to inelastic scattering.

CONCLUDING REMARKS

In conclusion, it should be pointed out that two previous series of experiments have been conducted by two separate groups of experimenters on proton damage to silicon solar cells as a function of proton energy (refs. 6 and 7). Denny and Downing observed that the damage to silicon solar cells supported a linear inverse energy dependence up to 100 MeV; however, Rosenzweig, Smits, and Brown observed that between about 8 and 40 MeV, the proton damage to silicon solar cells is almost unchanged. The results described in this paper do not agree with the results of either group. However, this paper has dealt with majority carrier removal rates and not minority carrier lifetime upon which the solar cell is dependent.

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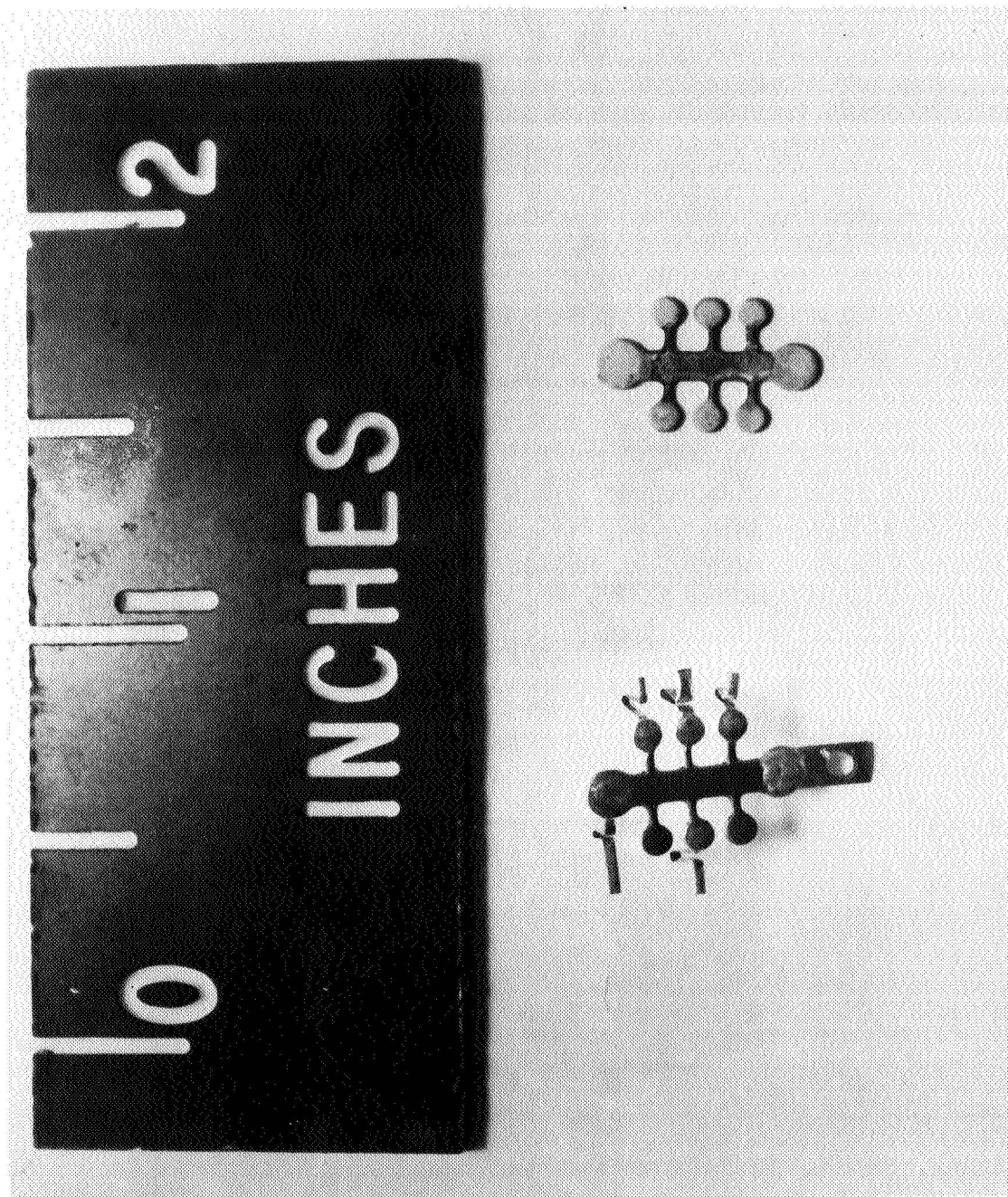


Figure 1.- Silicon sample.

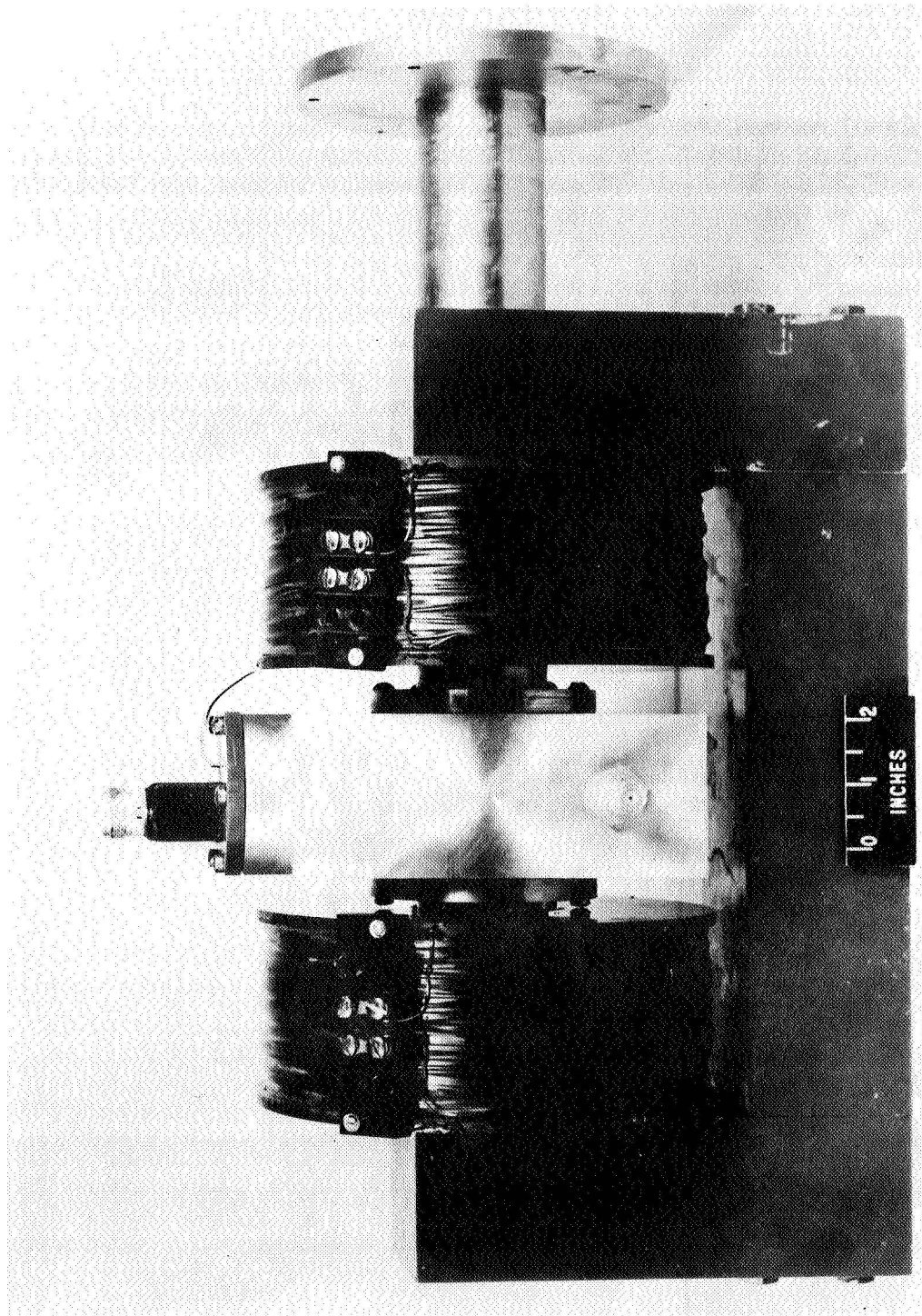


Figure 2.- Experimental setup.

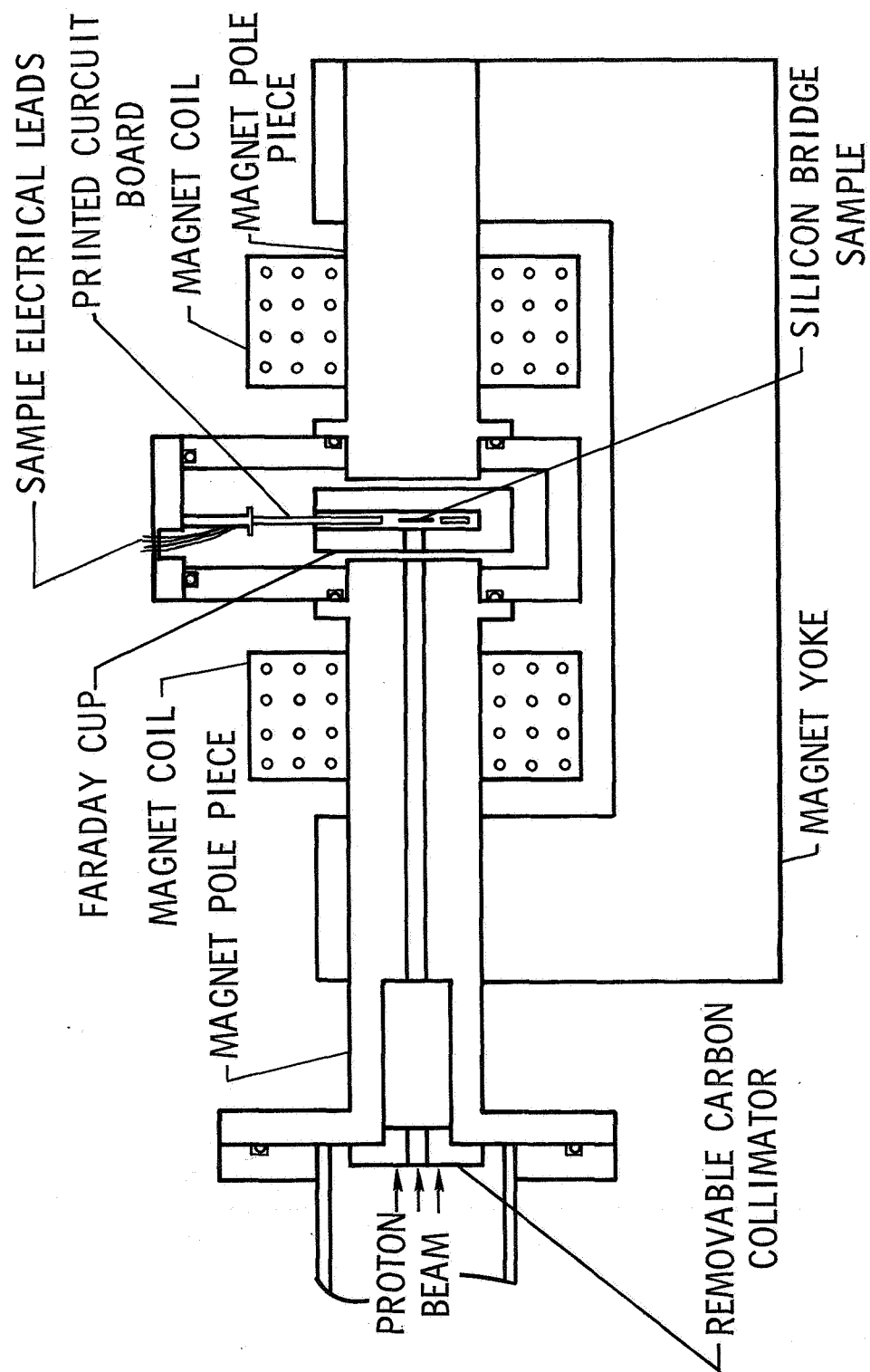


Figure 3.- Schematic of experimental setup.

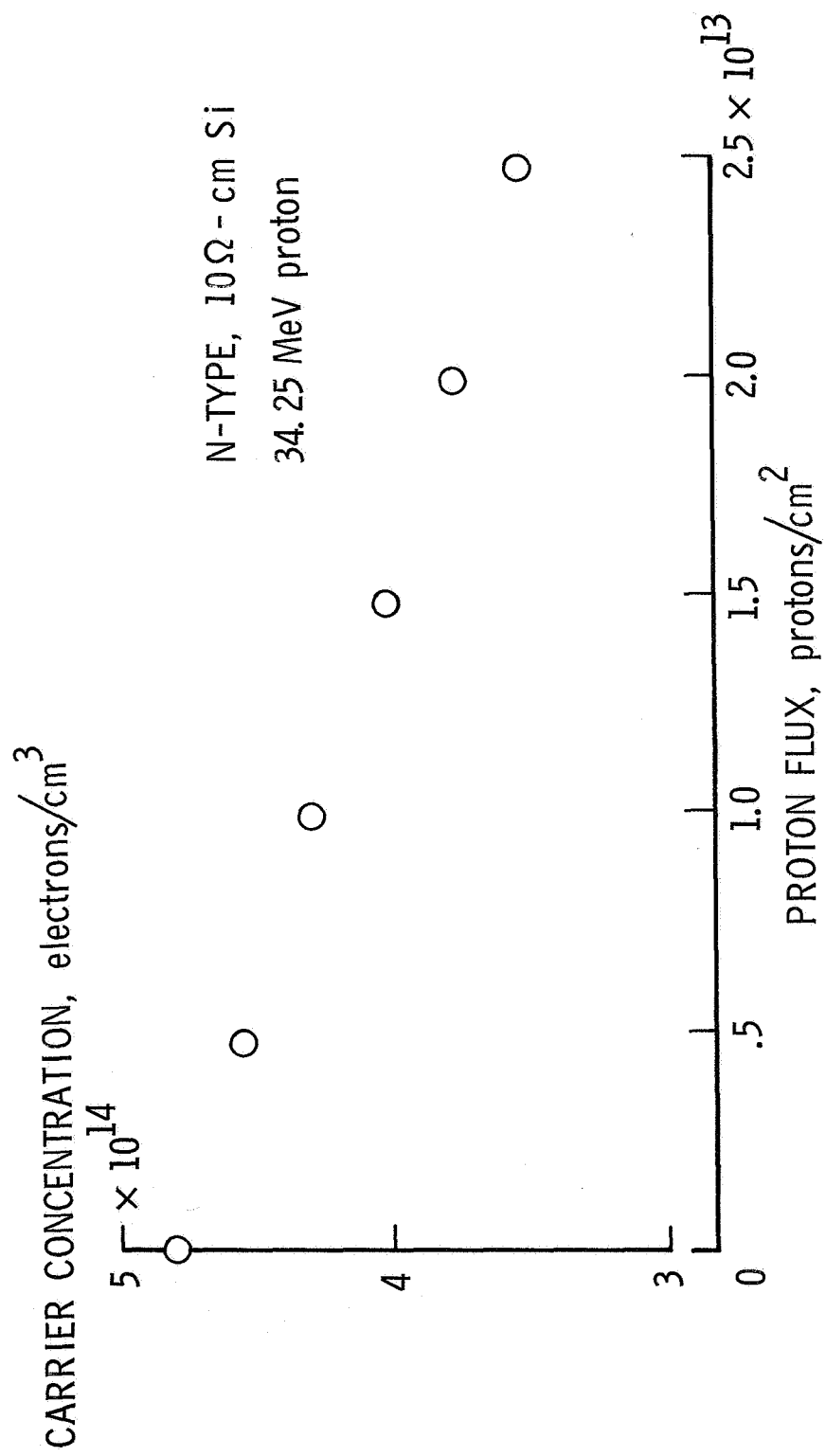


Figure 4.- Carrier concentration versus proton flux.

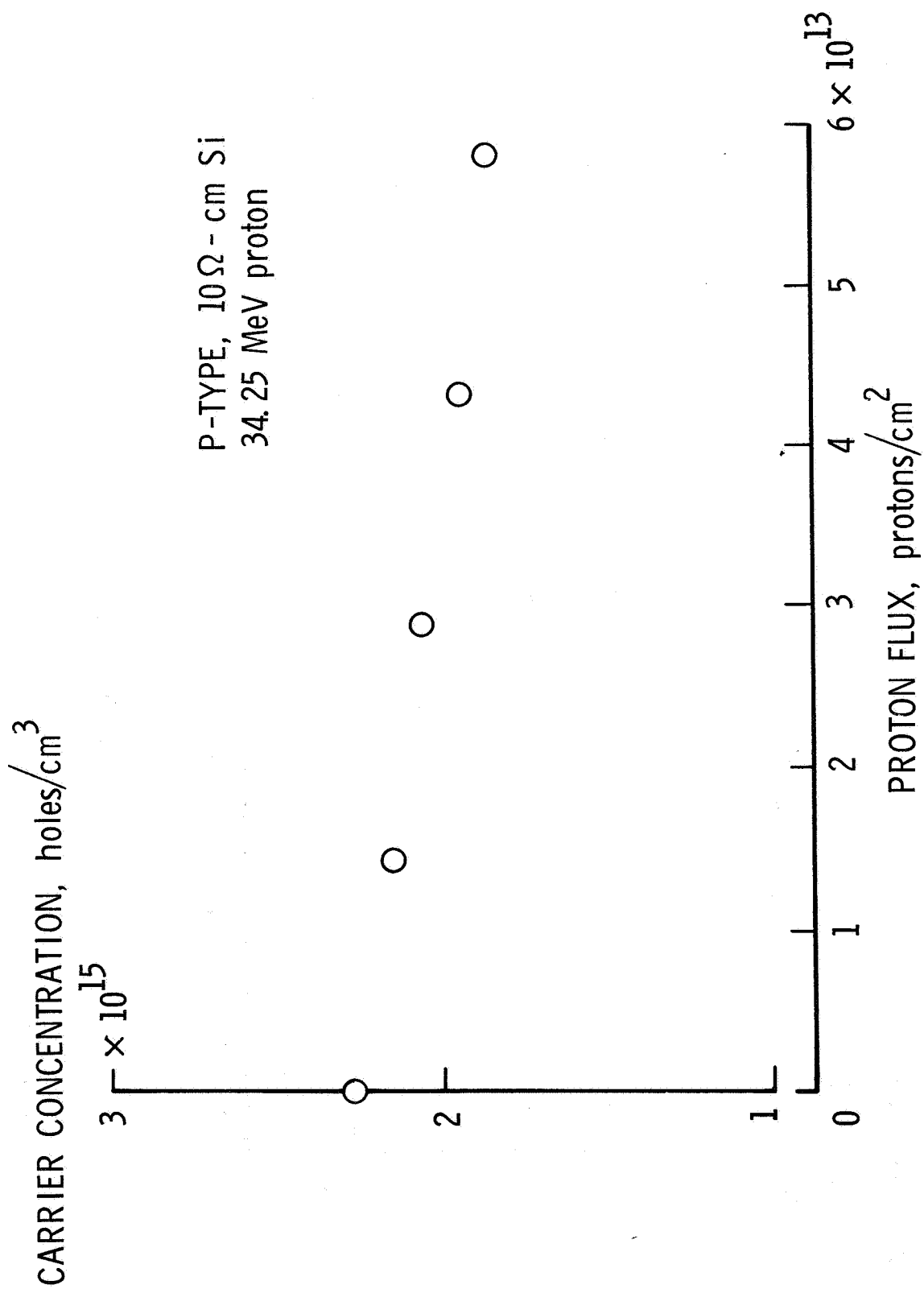


Figure 5.- Carrier concentration versus proton flux.

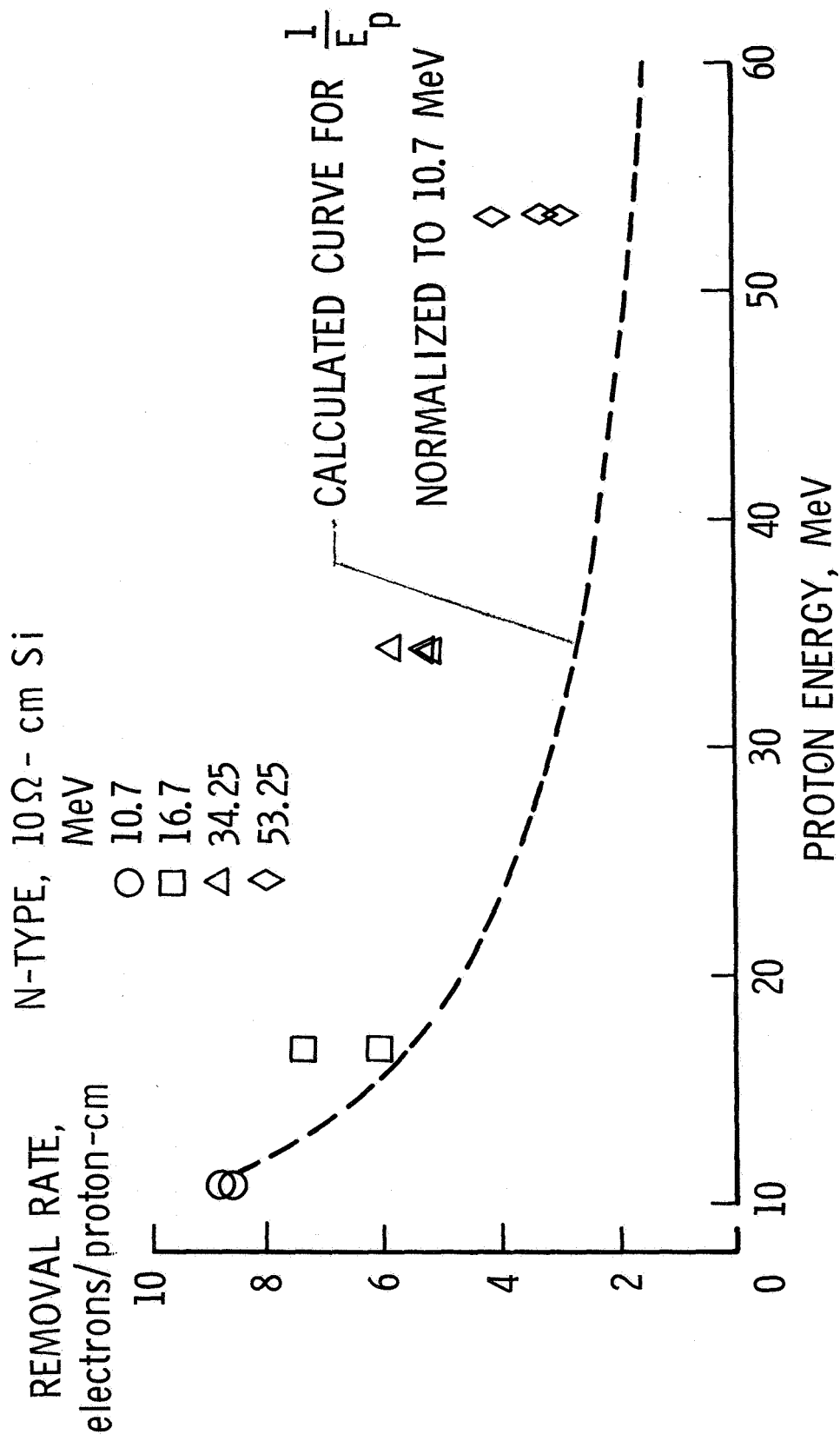


Figure 6.- Removal rate versus proton energy.

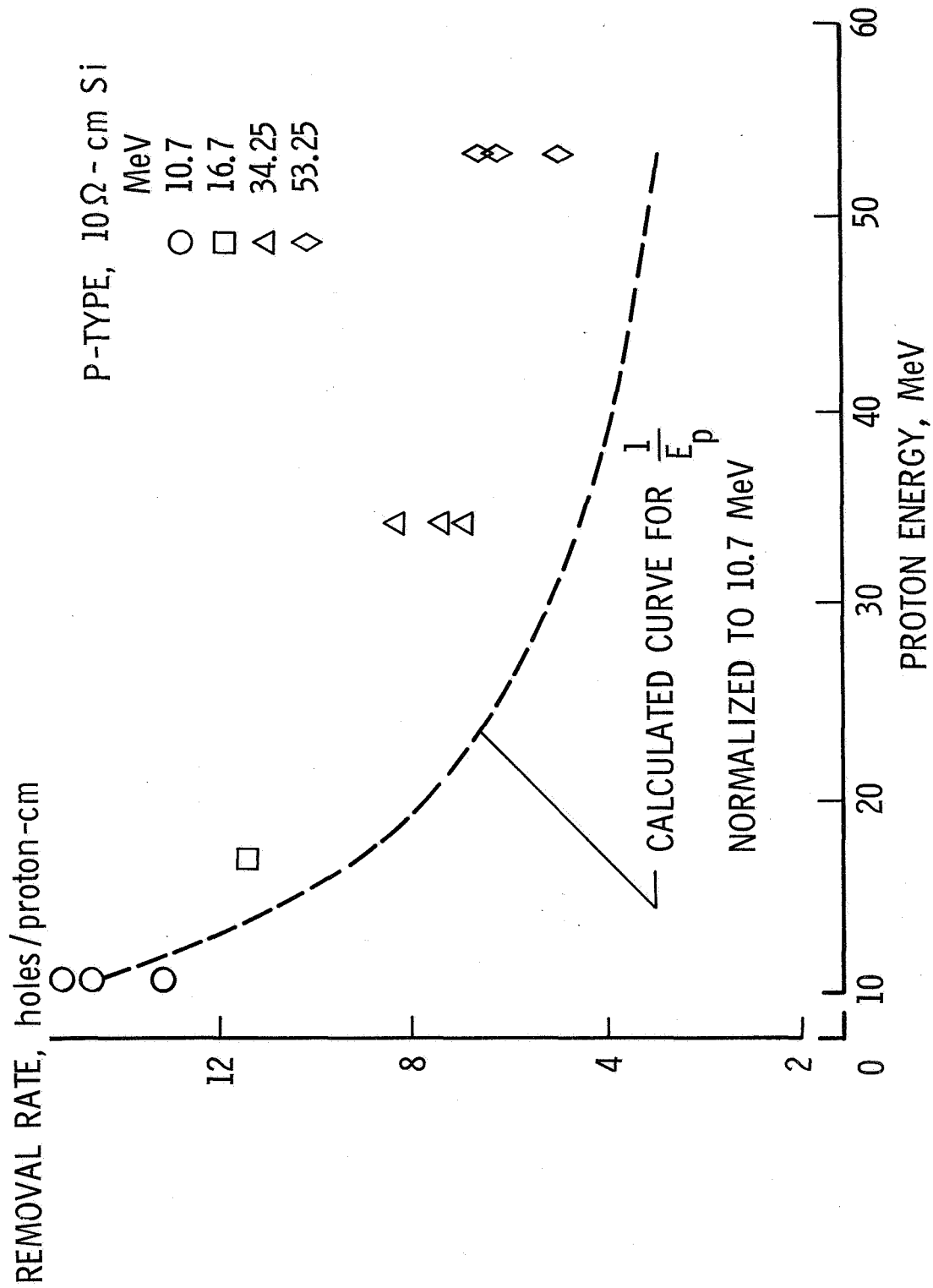


Figure 7.- Removal rate versus proton energy.